EVALUATING THE INTERNATIONAL STANDARD PROCEDURE FOR TESTING SOLAR COOKERS AND REPORTING PERFORMANCE

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Abstract—The international standard procedure for testing solar cookers and reporting performance was proposed at the Third World Conference on Solar Cooking (Avinashilingam University, Coimbatore, India, 6–10 January, 1997) and revised by the committee over the following months. The standard sets limits for environmental conditions, specifies test procedures and calls for performance to be reported in terms of cooking power (W). While this value, like the fuel economy rating of an automobile, is not a guarantee of performance, it does provide a useful tool for comparison. The entire standard is presented in this paper. It was evaluated both by using it to analyze data previously collected and by using it to test one of the solar cookers in the historical data set. The test standard cooking power curve clearly distinguishes between solar cookers of differing design. Estimates of solar cooker performance for different locations and dates are fairly consistent when the test standard is employed. The criteria of being easy to use and presenting data predictive of thermal performance are also satisfied.   Published by Elsevier Science Ltd.

1. INTRODUCTION

Increasing awareness of the growing global need for alternative cooking fuels has resulted in an expansion of solar cooker research and development. Using common units to measure performance facilitates communicating the results of promising experiments to other researchers around the world. The objective of this paper is to present and evaluate the solar cooker test standard proposed at the Third World Conference on Solar Cooking (Avinashilingam University, Coimbatore, India, 6–10 January, 1997). Evaluation will consist of determining if the standard is practical to use, if it differentiates between solar cooker designs, and if the results are repeatable.

2. ANTECEDENTS

Test standards already exist, but have not been widely employed in papers discussing solar cooker performance. The Indian standard used for deciding on subsidy (Anonymous, 1992) is for one specific design. It is based on the test standard proposed by Mullick *et al.* (1987). The standard proposed by Mullick is more complicated and less universal than the one being evaluated, though the characteristic curve they developed is a good predictive tool. In Europe, Grupp *et al.* (1994) employ a test procedure that presents much useful information. Though comprehensive, that test protocol may be difficult to replicate in less developed areas. The objectives of the standard being evaluated are to make testing as simple as possible, to present cooker potential in widely recognized units, and to obtain information that will be predictive of cooker performance. Because this international standard was developed by many people from many locations, it benefits from the collective wisdom of some of the industry's most experienced researchers.

3. THE STANDARD

Recognizing the need for both a common format by which researchers can share results and recognizing the need for a single measure of performance to facilitate consumers' selection of solar cookers, the test standard committee convened at Coimbatore on 9 January 1997 and agreed that:

The one figure best representing thermal performance is effective cooking power, which accounts for both different cooker sizes and heat gain rates. The unit of power with which most people are familiar is the Watt. The influence test conditions have on results can be minimized if uncontrolled variables are held to certain ranges.

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Therefore, the committee recommends the following test procedure and reporting format.

3.1. Uncontrolled (weather) variables

3.1.1. Wind. Conduct solar cooker tests when wind is less than 1.0 m/s at the elevation of the cooker being tested. If the wind is over 2.5 m/s for more than 10 min, discard the test data. Reason: heat loss is strongly influenced by wind velocity. Wind velocities less than 1.0 m/s help to maintain a heat loss coefficient close to the natural convection loss coefficient, yielding results that are more consistent and repeatable. If wind shelter is required, it must be designed so as to not interfere with incoming total radiation. (Note: future standards may include specific wind velocities. However, measuring and controlling wind adds complexity, conflicting with the goal of having a simple test repeatable anywhere.)

3.1.2. Ambient temperature. Conduct solar cooker tests when ambient temperatures are between 20 and 35°C. Reason: ambient temperature extremes experienced in one location may be difficult to replicate at another location. Cooking power is influenced by temperature difference. A range of 15°C keeps variability moderate, yet permits testing in most locations for at least half the year. Unavoidable exceptions need to be noted.

3.1.3. Pot contents temperature. Record data for water temperatures between 40 and 90°C. Reason (low end): pot contents must be above ambient for there to be heat losses. Reason (high end): boiling temperature varies with elevation, and latent heat of vaporization severely depresses apparent cooking power as water nears boiling. Avoiding the upper limit reduces the probability of having anomalies in the data.

3.1.4. Insolation. Available solar energy is to be measured in the plane perpendicular to direct beam radiation (the maximum reading) using a radiation pyranometer. Variation in measured insolation greater than 100 W/m^2 during a 10-min interval, or readings below 450 W/m^2 or above 1100 W/m^2 during the test render the test invalid. Reason: maintaining moderate fluctuations in insolation levels reduces the variability caused by thermal inertia effects. Taking readings within 65% of the standard insolation level (which is 700 W/m^2) reduces errors introduced by adjusting cooking power for available insolation. It is expected that most locations will meet these criteria. If not, exceptions need to be specially noted.

3.1.5. Solar altitude and azimuth. The committee strongly recommends that tests be conducted between 10:00 and 14:00 solar time. Reason: solar zenith angle is somewhat constant at midday, and the difference between insolation measured in the plane of the cooker aperture and the plane perpendicular to direct beam radiation will vary least. Exceptions necessitated by solar variability (presence of clouds at midday during monsoon season) or ambient temperature (midday is too hot) must be specially noted.

3.2. Controlled (cooker) variables

3.2.1. Loading. Cookers are to have 7 kg water/m^2 intercept area distributed evenly between the pots supplied with the cooker. Intercept area is defined as the sum of the reflector and aperture areas projected onto the plane perpendicular to direct beam radiation. The beam radiation zenith angle may be averaged over the test period. Tracking may compensate for the beam radiation azimuth angle. These two strategies should result in a constant intercept area, facilitating load calculations. Reasons: water closely resembles food in density and specific heat, but is more consistent. Intercepted radiation is the best measure of available energy. Thermal performance is sensitive to loading rate. This particular value is close to the various loading rates cited in previous publications.

3.2.2. Tracking. Azimuth angle tracking frequency must be appropriate to the cooker's acceptance angle. Box-type cookers typically require adjustment every 15 to 30 min or when shadows appear on the absorber plate. Parabolic-type units may require more frequent adjustment to keep the solar image focused on the pot or absorber. With box-type cookers, zenith angle tracking may be unnecessary during a 2-h test conducted at midday. Testing should be representative of anticipated consumer habits.

3.2.3. Temperature sensing. Thermocouples are recommended for their low cost, accuracy and rapid response. Use pot(s) supplied with the cooker. If unavailable, use inexpensive aluminum pots most likely to be employed by the consumer. Thermocouple junctions should be immersed in the water in the pot(s) and secured 10 mm above the pot bottom, at the center. Thermocouple leads are to come through the pot lid (or wall above the

water line) inside a thermally nonconductive sleeve that will protect the thermocouple wire from bending and from temperature extremes. Secure the sleeve with silicone caulk to reduce vapor loss. Reasons: proper thermocouple placement can minimize errors that might be caused by thermal stratification and sensor intrusion into the pot. The thermal storage capacity of inexpensive aluminum cooking pots is insignificant compared to the thermal storage capacity of the water contained by them.

3.3. Test protocol

3.3.1. Recording. The average water temperature (°C) of all the pots in one cooker is to be recorded every 10 min, to one tenth of a degree if possible. The solar insolation (W/m^2) and ambient temperature are recorded at least as frequently. Record and report the frequency of attended (manual) tracking, if any. Report azimuth angle(s) during the test. Report the test site latitude and the date(s) of testing. Reason: ten minutes is a long enough time that the minor fluctuations in heat loss due to ambient temperature and wind variability are expected to be negligible. Ten minutes is a short enough time that the heat gain variability due to gradual sun angle changes may be considered constant during the interval.

3.3.2. Calculating cooking power. The change in water temperature for each 10-min interval is to be multiplied by the mass and specific heat capacity (4186 J/kg K) of the water contained in the pots. Dividing this product by the 600 s contained in a 10-min interval yields the cooking power in Watts. Reason: solar cookers must heat food, and sensible heat gain in a cooking pot is the best measure of a cooker's ability to effectively heat food.

3.3.3. Calculating interval averages. The average insolation, average ambient temperature, and average pot contents temperature are to be found for each interval.

3.3.4. Standardizing cooking power. Cooking power for each interval is to be corrected to a standard insolation of 700 W/m^2 by multiplying the observed cooking power by 700 W/m^2 and dividing by the average insolation recorded during the corresponding interval. Reason: to facilitate the comparison of results from different locations and dates.

3.3.5. Temperature difference. Ambient temperature for each interval is to be subtracted from the average pot contents temperature for each corresponding interval. Reason: heat loss increases with the difference in temperature between the solar cooker interior and the cooker's surroundings; pot contents temperature correlates to cooker interior temperature.

3.3.6. Plotting. The standardized cooking power (W) is to be plotted against the temperature difference (°C) for each time interval.

3.3.7. Regression. A linear regression of the plotted points is to be used to find the relationship between cooking power and temperature difference in terms of intercept (W) and slope (W/°C). At least 30 observations are required. The coefficient of determination (R^2) or proportion of variation in cooking power that can be attributed to the relationship found by regression should be better than 75% or specially noted. Reasons: statistical measures of goodness of fit for the regression line require a fairly large sample, and systematic errors are less likely to be repeated on different days. Excessive experimental error may invalidate the test.

3.3.8. Single measure of performance. The value for standardized cooking power (W) is to be computed for a temperature difference of 50°C using the above determined relationship. Reason: one single number in common units familiar to most consumers best facilitates the comparison of different devices. A temperature difference of 50°C strikes a balance between overemphasis on the start-up cooking power (where concentrating ovens are strongest) and stagnation temperature (where box cookers tend to be superior) and is just below that critical temperature where cooking begins to occur, the temperature when a solar cooker succeeds or fails. Note: for product labeling and sales literature it is strongly recommended that this number be calculated from a regression found by an independent laboratory using a statistically adequate number of trials. While this value, like the fuel economy rating of an automobile, is not a guarantee of performance, it provides consumers with a useful tool for comparison and selection.

3.3.9. Reporting. Plot the relationship between standardized cooking power and temperature difference, and present the equation. State the cooking power (standardized) at a temperature difference of 50°C.
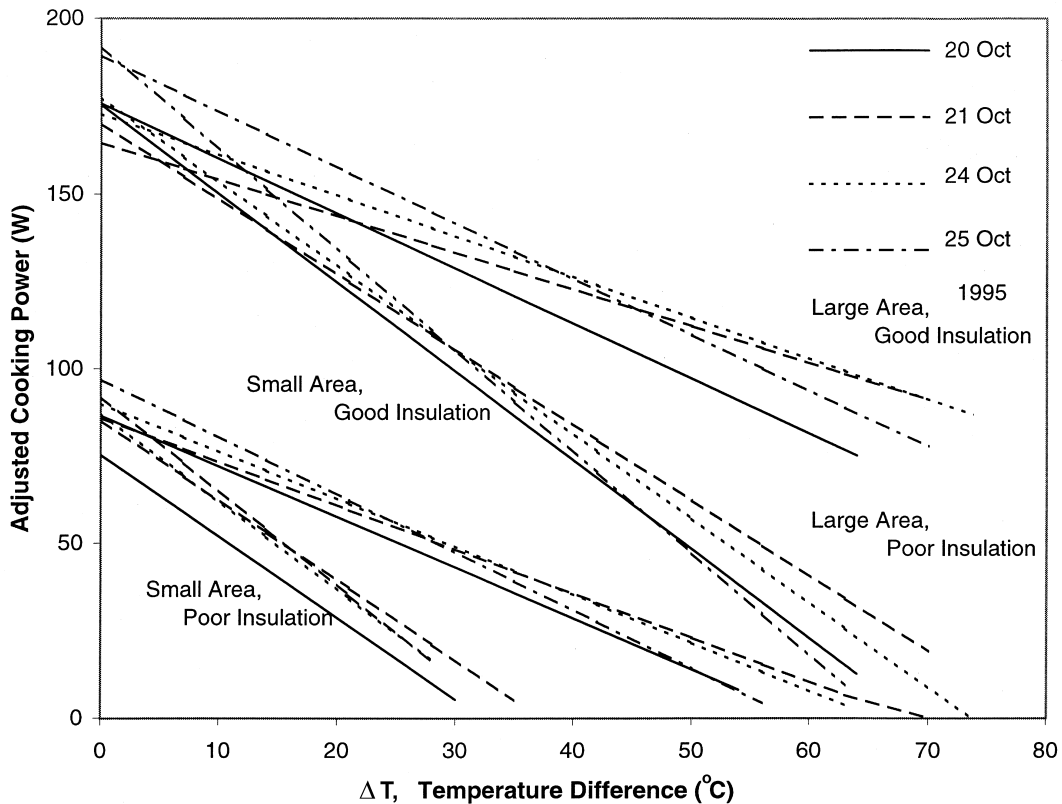
Fig. 1. A comparison of cooking power curves for four cookers with two levels of intercept area and heat loss. International standard was applied to data recorded over 4 days in 1995.

4. PROCEDURE

4.1. Comparison of cookers

Data from prior research (Funk and Larson, 1998) was manipulated following the above protocol. The prior data set was large, providing a statistically adequate number of observations. Unfortunately, not all of the above procedures had been strictly adhered to (the standard had not been written yet). Loading rates varied from 4.1 to 13.6 kg/m^2. The test standard requirements for temperature range and insolation were applied, limiting the available data to between 15 and 43 observations for each oven on each day. Adjusted cooking power and temperature difference were calculated every 10 min for each solar cooker from a 2×2 factorial experiment. The two variables were solar intercept area and heat loss coefficient. The two levels of area were 0.293 m^2 (one reflector) and 0.966 m^2 (reflectors arranged in a truncated pyramid around the same sized cooking chamber). The two levels of heat loss were 1.2 W/°C (foil lined cardboard box with single glazing) and 1.9 W/°C (glazing removed). These heat loss coefficients expressed with respect to glazing area were 4.8 and 7.6 W/m^2 °C,

Table 1. Comparison of four cookers with two levels of intercept area and heat loss

Solar cooker design	Date (Oct 1995)	Cooking power regression equation		Adjusted cooking power (W) at 50°C ΔT
		Intercept (W)	Slope (W/°C)	
Large area, Good insulation	20	176	−1.57	97
	21	165	−1.05	112
	24	173	−1.17	115
	25	189	−1.60	110
	Average	175.75	−1.35	108.50
	S.D.	9.98	0.28	7.94
Large area, Poor insulation	20	175	−2.54	48
	21	170	−2.16	62
	24	177	−2.41	57
	25	192	−2.90	47
	Average	178.50	−2.50	53.50
	S.D.	9.47	0.31	7.23
Small area, Good insulation	20	87	−1.45	14
	21	86	−1.26	23
	24	90	−1.37	21
	25	97	−1.65	14
	Average	90.00	−1.43	18.00
	S.D.	4.97	0.16	4.69
Small area, Poor insulation	20	75	−2.33	
	21	92	−2.71	Not applicable
	24	87	−2.52	
	25	85	−2.29	
	Average	84.75	−2.46	
	S.D.	7.14	0.19	

respectively. Testing of the four different designs was replicated on 4 days.

4.2. Comparison of dates and locations

One cooker was tested according to the standard in November of 1998, with automated data recording in Las Cruces, New Mexico. The results were compared with data taken using the same cooker 18 months earlier, in May of 1997, with hand held instruments in Tucson, Arizona. This particular cooker was constructed of thermoformed plastic and aluminum, with polyisocyanurate foam insulation. It had no reflector. The cooker held five pots each containing 424 g of water and a thermocouple junction. Tucson and Las Cruces are at the same latitude but different elevations (728 and 1183 m, respectively). The zenith angle in May ranged from 30 to 13 degrees, and in November remained between 51 and 52 degrees during testing (2 h bracketing noon local time).

5. RESULTS

5.1. Comparison of cookers

Fig. 1 illustrates the clear distinction made between the design factors by the cooking power plots. The two cookers with large collector areas both enjoyed a high y-intercept (initial cooking power). The two cookers with a high heat loss coefficient both suffered a steep negative slope. Of special interest is the fact that the slope and intercept values are independent of each other. The slope of the cooking power regression line correlates to the heat loss coefficient independent of the solar intercept area. And where the heat loss coefficient influence is zero (at the intercept, where the temperature difference is zero) the cookers with the same intercept area have roughly the same adjusted cooking power. Linear regression was performed on each of the resulting 16 data sets. The regression equation coefficients and the adjusted cooking power at 50°C for each cooker and date are presented in Table 1. The coefficient of determination (R^2) values averaged 82% and exceeded 85% (satisfying the standard) for all but one cooker.

5.2. Comparison of dates and locations

Fig. 2 illustrates a consistency in results for the same cooker tested on different dates and at different locations. Cooking power (W) as a function of temperature difference (°C) in 1997 at Tucson was:
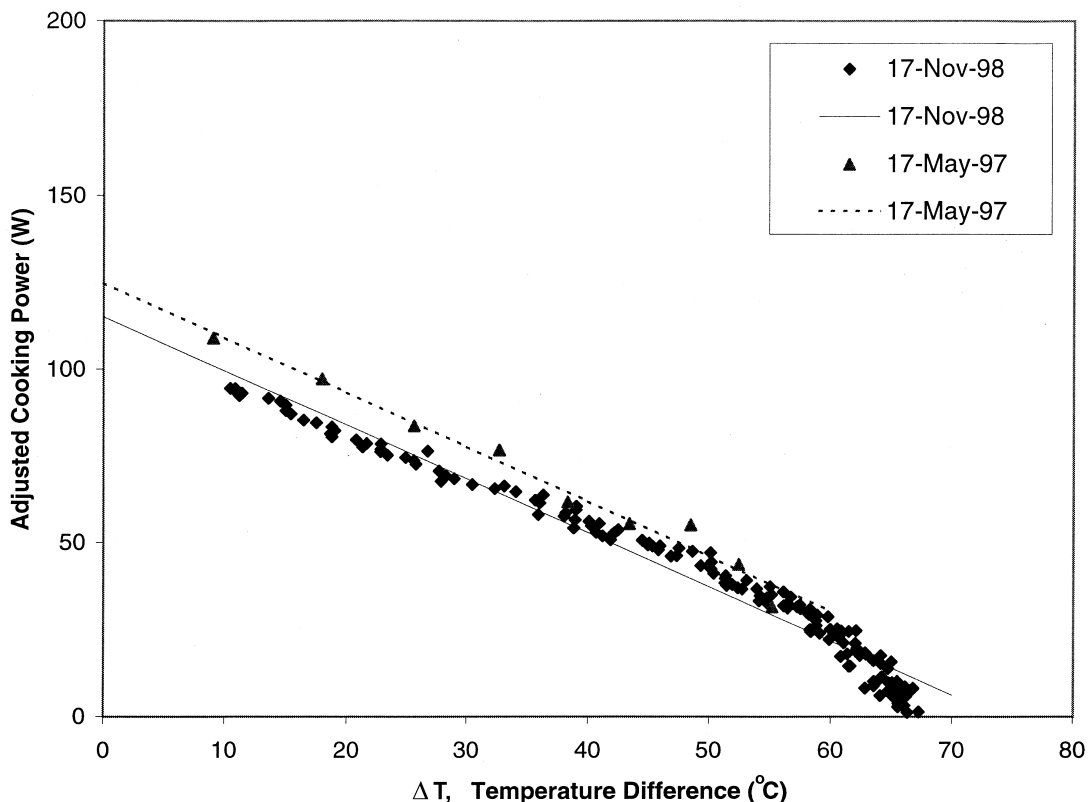

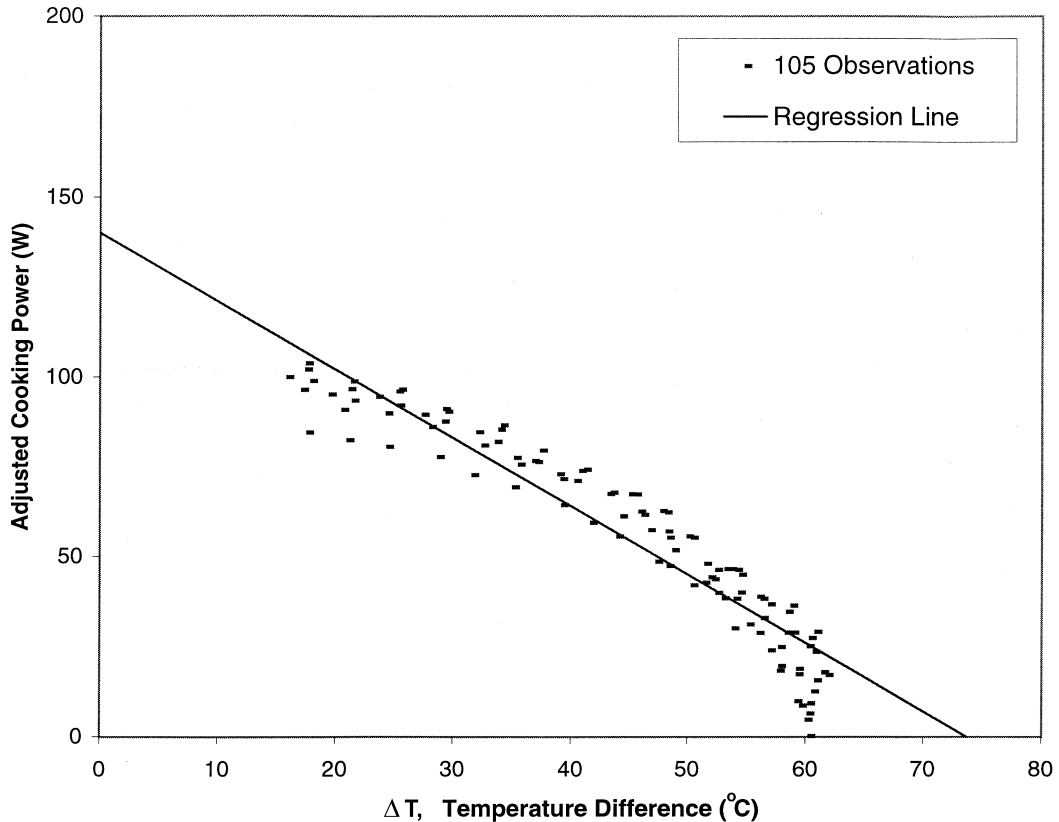Fig. 2. A comparison of cooking power curves for the same cooker at two different times and locations.

Fig. 3. A comparison of the cooking power curve regression line to its base data.

$$P = 125 - 1.58\,\Delta T. \tag{1}$$

Cooking power (W) as a function of temperature difference (W/°C) in 1998 at Las Cruces was:

$$P = 115 - 1.56\,\Delta T. \tag{2}$$

The slope of the cooking power regression line did not change. The intercept fell slightly. This is probably due to the deterioration (scratches, dirt) of the acrylic glazing with time. If wind had been a factor, the slopes would have differed. Cooking power at a temperature difference of 50°C was estimated to be 46 and 37 W in 1997 and 1998, respectively. On both test days the sky was clear. The linear regression coefficient of determination (R^2) for both dates exceeded 95%, satisfying the standard.

regression has a good fit ($R^2 = 90\%$) but one could argue that the relationship is probably non-linear. Most likely this is due to the increasing influence of radiative heat loss at elevated temperatures. For small temperature differences convective and conductive heat losses (first order equations) dominate. As the temperature of the black cooking vessels and black interior of the cooker differ appreciably from their surroundings, the radiative loss will increase more rapidly, this being a function of the difference between the fourth power of the absolute temperatures of the interacting surfaces. However, polynomial regression of the data does not substantially improve the coefficient of determination. A first order approximation is adequate for temperature differences of this magnitude.

6. DISCUSSION

Fig. 3 compares a cooking power regression line for a cooker with intermediate intercept area and heat loss coefficient levels to the 106 observations from which it was derived. The linear

7. CONCLUSION

The proposed international standard for testing solar cookers and reporting performance was applied to historical solar cooker test data to show that it is a useful tool for evaluating the relative

performance of different designs. The standard was easy to apply. The resulting solar cooker power curve is a useful device for interpreting the capacity and heat retention ability of a solar cooker, the two parameters most important to performance. The cooking power curve found by using the international test standard appeared to be independent of location and date provided the protocol could be followed (clear skies, low wind).

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